Modeling Respiratory Anatomy and Physiology in VR*

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In trauma, many injuries impact anatomical structures, which may in turn affect physiological processes—not only those processes within the structures, but ones occuring in physical proximity to them as well. Our goal is to endow a 3D anatomical model with physiological mechanisms to demonstrate such effects. Our approach couples deformable object simulation for organs with physiological modeling, in a way that supports three-dimensional animated simulation. We demonstrate our approach through our current model of respiratory mechanics in a virtual 3D environment. Anatomical models that can capture physiological and pathophysiological changes can serve as an infrastructure for more detailed modeling, as well as benefiting surgical planning, surgical training, and general medical education.

INTRODUCTION

Trauma frequently involves structural changes to the body, such as fractures, hemorrhage, and ruptured organs, which may affect multiple body systems. When the physical topology of body systems changes, we need to reconsider the dependencies among them to predict the effects of injury. Such assessment and resulting behavior will depend crucially on physical proximity and contact forces.

Our goal is to integrate mechanical models for body systems with other physiological process models to demonstrate normal behavior and interaction with neighboring body systems resulting from trauma.

For example, a *flail chest* is the condition in which segments of the ribcage become detached. During breathing, the flail section moves paradoxically to the rest of the ribcage because that section is influenced by forces different from those moving the remainder of the ribcage. This result is predictable from a mechanical model of the respiratory system. In a *tension pneumothorax*, accumulation of air within the intrapleural space results in pressing the mediastinum against the opposite lung. With the resulting increased pressure on the inferior vena cava in the mediastinum, the vein collapses and impedes venous return to the heart. This result is predictable from a model that considers the dynamics of anatomy and physiology.

An accurate simulation of the body, then, requires an approach that integrates a realistic, 3D structural model, deformable body dynamics, and physiological dynamics (biochemical, electrical, etc.)—a *functional anatomy* that explicitly links the anatomical structures with physiological behavior of the body.

To make our models appropriate to clinical situations, we base our mechanical models on observable physiological variables, such as pleural and body surface pressure. However, these are only indirectly related to the real mechanical forces (vectors), so we need to give them a 3D interpretation. For our initial models, we apply scalar pressure values along vectors that approximate the way the shape changes.

This paper describes the current state of our ongoing effort[1] and the methodologies we are developing for our virtual environment. The respiratory system is a good starting point because its function depends on mechanics and it can interact with other systems as a result of mechanical behavior. Our current interest is in using these models for illustrating fundamental medical concepts involving structure and function, but they may have uses for their predictive capabilities and serve as an infrastructure for more detailed modeling.

BACKGROUND

Interactive medical applications in Virtual Reality are relatively new, owing to new developments in computer hardware. Medical modeling, on the other hand, has an illustrious history within bioengineering.[2] More recently, interest has grown in Computer Science, specifically within the Artificial Intelligence (AI) community.[3, 4] This section reviews some of the approaches aimed at surgical simulation and medical education in Virtual Reality (see Emerson, Prothero, and Weghorst[5] for an extensive bibliography).

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Satava[6] argues that Virtual Reality will have a significant impact on medical education and training. Through three-dimensional visualization, programs will help medical students understand important physiological principles or basic anatomy.

While there is a growing body of multimedia programs for medical instruction, 'simulation' is typically limited to relatively simple calculations about high-level physiological behavior. With respect to anatomy, most atlases are limited to one or a few viewing perspectives (recent efforts,[7, 8] though, incorporate navigation in 3D). The September/October 1993 issue of *Syllabus* is devoted to educational technology products that incorporate simulation, highlighting several designed for medical education. None of these systems has a realistic model of the biomechanical and physiological properties of the tissues and organs they are presenting to students, where organs move or deform in response to force.

Medical professionals will evaluate virtual reality medical applications on their fidelity to actual experience. For surgical simulations, imprecise anatomical representations and implausible behavior will detract from the realism and believability of the virtual experience.[9] Since the visual impact of simulators is critical, much effort has been focused on providing realistic images, through techniques such as interactive laser discs, intense computer graphics simulations, and the integration of actual images with superimposed computer graphics.[10]

Cover, Ezquerra, O'Brien et al[11] review current deformable object modeling methods to contrast with their own physics-based methodology based on energy-minimizing surfaces for organ models. They stress that existing systems do not have visually-realistic graphics or the interaction is unrealistic or cannot be achieved at real-time rates.

An exciting prospect for surgical simulation and education involves potential uses for the data collected in the Visible Human Project.[12] The Visible Human Project is an endeavor to create a complete, anatomically detailed, 3-D representation of the male and female body, from CT, MR, and cryosection images. Part of the long-term goals for the Project is to develop basic research into representation of structures, particularly encoding the connection between structural-anatomical to functional-physiological knowledge. For our purposes, such data could provide organ models and realistic-looking images to map onto them, using real-time texture-mapping hardware.

Dumay[13] notes that today, the first generation of virtual surgical simulators have been developed with the focus on rendering human anatomy, neglecting physiological and pathophysiological modeling. Our aim is to link foundational physiological models that express mechanical behavior (and ultimately chemical and neurological functions) with a structurally-accurate anatomical model.

RESPIRATORY SYSTEM MODELING

Our work consists of coupling physiological process simulation with deformable object modeling to give behavior to our virtual organs. There are two main pieces to this work, the anatomical simulation, namely deformable object and environment modeling, and the physiological simulation, namely computation of pressure, volume, and other physiological variable changes. This section reviews our approaches to each and discusses how they communicate.

Anatomical Modeling

Our original intent was to use the Finite Element Method.[1] However, computational demands of real-time physiological simulation have led us to using lumped-parameter modeling.[14] Though it is a relatively simple physically-based modeling approach, it is quite versatile. In this methodology, objects are represented as a surface or volume mesh consisting of nodes (concentrations of mass) and interconnections (damped springs). The springs hold the object together. As an object is deformed, internal energy builds in the springs to restore the object to its resting shape.

Our objects are responsive to three types of forces: (1) *internal forces*, such as those arising from internal energy; (2) *contact forces*, or forces that apply as a result of pressure gradients or spatial interaction; and (3) *body forces* that apply to all objects in the environment, such as gravity. We are currently experimenting with different methods for collision detection and resolution.

Physiological Modeling

This paper introduces our methodology by considering the mechanics of breathing. Mechanics describes the relation among forces, displacements, and their derivatives. In discussing respiratory mechanics modeling, Ligas and Primiano[15] distinguish two model paradigms: classical and formal mechanical modeling. The distinction refers to the form of the model and variables. In *classical models*, forces and displacements are not represented as vectors. Instead scalar variables such as volume represent generalized displacement, and pressure differences represent generalized forces. *Formal mechanical models* involve sets of vector equations relating forces and displacements. Formal mechanical models are applications of continuum mechanics to the respiratory system.

Classical models are based on *observable* variables such as airway pressure, body surface pressure, chest wall volume change, etc., whereas formal mechanical models require more detailed measurements that may not be readily accessible (e.g., specific tissue segment displacements).

The models we are building for other physiological mechanisms and systems reflect traditional bioengineering approaches for simulation, such as those described by Rideout.[2] They are expressed as ordinary differential equations and solved using conventional numerical methods.

Current Models. The basic equation for the classical approach to respiratory mechanics modeling relates a sum of pressure differences to a function essentially of volume and its derivatives

$$\sum \Delta P = f(V, \dot{V}, \ddot{V}, \ldots). \quad (1)$$

We have made approximations that only involve up to the first derivative of volume. When we consider respiratory manuevers with small displacements, we model the change about an operating point for our variables. See Ligas and Primiano[15] for details.

We began by modeling a single, idealized lung during quiet, normal breathing, with constant compliances and resistances for the lung and chest wall (a unit that represents the ribcage, the diaphragm-abdominal combination, and the muscles involved in respiration). The model for this is:

$$v_l = v_{cw} \quad (2)$$

$$p_{pl} - p_{bs} = -\Delta P_m + v_{cw} / C_{cw} + R_{cw}\dot{v}_{cw} \quad (3)$$

$$p_{ao} - p_{pl} = v_l / C_l + R_l\dot{v}_l \quad (4)$$

where the lowercase letters represent changes about an operating point for pressures (p) and volumes (v) of the lung (l), chest wall (cw), pleural space (pl), body surface (bs), and airway (ao). The uppercase letters represent resistance (R) and compliance (C) constants and the term ΔP_m represents the force exerted by the chest wall muscles cast as an effective pressure difference. Equation (2) represents the constraint that the change in chest wall and change in lung volume are equal, since the change in the volume of the intrapleural fluid is zero (incompressible). Equation (3) represents the forces acting on the chest wall, and Equation (4) represents the forces acting on the lung.

We have also applied Equations (3) and (4) to modeling pneumothoraces. A pneumothorax is a pathological condition in which air enters the space between the visceral and parietal pleura. Normally, this space is occupied by a small amount of fluid. Our goal is to model at least three types of pneumothoraces: (1) closed (simple) pneumothorax, in which some air has gotten trapped between the pleura, possibly impeding normal respirations; (2) an open sucking chest wound, in which one or more holes exist in the chest wall that permits air into and out of the pleural space; and (3) a tension pneumothorax, in which one or more holes in the chest wall exist that permits air to enter the pleural space but not exit.

The equations for each type of pneumothorax are not very different from one another. When air enters the pleural space, the change in volume of the pleural space is no longer zero, so we replace Equation (2) by Equation (5) that factors in the change in pleural volume to the change in volume of the chest wall:

$$v_l + v_{pl} = v_{cw}. \quad (5)$$

Equations (3) and (4) are also part of our pneumothorax models. However, we need to add an equation that describes the change in pleural volume and pressure as a result of any air entering or leaving the pleural space through the passage. We add Equation (6) that relates the pressure gradient across the interface to the change in volume of the intrapleural space:

$$p_{bs} - p_{pl} = R_{pl}\dot{v}_{pl}. \quad (6)$$

Therefore, our basic pneumothorax model consists of Equations (3)–(6). From this we can describe the effect of gas entering the pleural space, but we have not yet included the effect of mediastinal displacement in the severe open sucking chest wound and tension pneumothorax.

We are designing our virtual respiratory system from the 'bottom up'—focusing on modeling the mechanics of breathing, which in turn can provide the support for higher-level respiratory physiology such as oxygen uptake. Our cardiovascular model encodes pressures and volumes that result in blood flow. We expect that these models could be interfaced functionally (as well as mechanically) to support biochemical processes, such as blood gas simulations.

Integration

Our physiological modeling consists of scalar equations relating pressures and volumes. Our deformable object modeling, on the other hand, consists of vector equations. To integrate these, we must give the generalized force (pressure difference) a geometric interpretation. Currently, we apply these forces to the lung along vectors chosen to approximate the deformation of the lung, as it expands and contracts. A more accurate approximation would apply the forces along surface normals. We will achieve this by adjusting the viscoelastic properties of our 3-D model.

Our integration relates pressure gradients to 3-D forces and volumes predicted from the solution to the model equations to volumes computed from our 3-D anatomy. For anatomical modeling, pressure gradients derived from the mechanical simulation are the forces that influence shape and motion. For physiological modeling, we simulate the mechanics in terms of pressures and volumes, and can express other physiological behavior in terms of their effect or dependence on pressure and volume. For example, we could simulate biochemical stimuli that trigger neurological control mechanisms, which then influence our mechanical model (e.g., increasing or decreasing respiratory rate).

PRELIMINARY RESULTS

The work done to date consists of populating our virtual environment with deformable objects (lungs), experimenting with collision detection and resolution methods for object interaction, and creating physiological simulations. As the simulation proceeds, the operator sees the organs expand and contract in response to the applicable forces, as well as concurrent plots of physiological variables.

Anatomical Modeling

We have built routines for populating a virtual environment with our deformable organ models, based on the lumped-parameter methodology discussed previously. We are currently working on robust routines for determining and resolving interaction among the objects. We can gain some assistance from physics and the physically-based modeling literature, but we face interesting challenges because some deformable anatomical parts can take irregular shapes. This complicates the collision detection and resolution routines.

For example, we can see in Figure 1 how the inflated lung does not quite fill the spaces in the chest wall, particularly those that are narrow or irregularly-shaped.

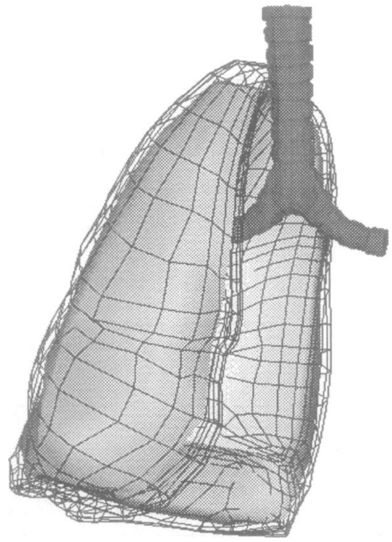


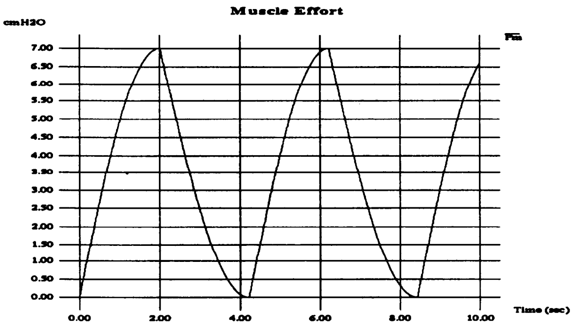
Figure 1. Deformable right lung within chest wall.

Physiological Modeling

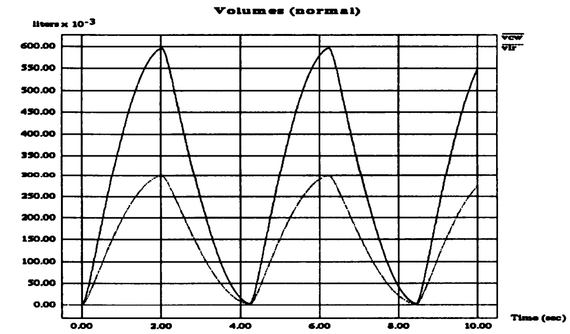
Figures 2(a)-(c) show the results for our normal, quiet breathing model for two lung compartments but a single chest wall and pleural space. Figure 2(a) shows the muscle pressure driving the chest wall, while 2(b) shows the change in volumes. It shows the chest wall reaching about 600ml, which is the sum of the lung volume change (we show the volume of the right lung in Figure 2(b), reaching about 300ml).

Figure 2(c) shows the change in pleural pressure (the function reaching the lower value), and the change in (right) alveolar pressure ($p_{alv} = p_{ao} - R_l \dot{v}_l$, where change in airway pressure is typically zero, $p_{ao} = 0$). The dominating, driving force in the model is a quarter-sine wave that we created to simulate the muscle forces (Figure 2(a)). The values for resistances and compliances were obtained from the literature, except the chest wall resistance which was estimated.

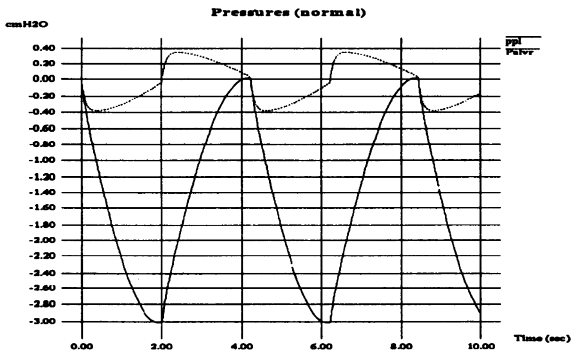
The reader will note how the change in pleural pressure becomes more negative as the chest wall expands. The graph also shows how the alveolar pressure changes to initiate air flow. It is important to remember that the equations represent and resulting graphs show the change about an operating point and not an absolute value for volume or pressure.



(a)



(b)



(c)

Figure 2. Normal, quiet breathing; (a) shows ΔP_m, (b) Volumes: shows chest wall (higher) and right lung volume changes, (c) Pressures: shows pleural pressure (lower) and right alveolar pressure changes.

CONCLUSION

We have presented early work on respiratory mechanics that addresses both anatomical and physiological simulation in a three-dimensional, virtual environment. Our methodology incorporates physically-based modeling methods with traditional bioengineering approaches to physiological simulation. Unlike other projects we have reviewed, we are exploring fundamental issues about physiological modeling and are concerned about making explicit the link between anatomical structures and physiological behavior. Since the relationship between anatomy and physiology is so critical in understanding normal and pathological processes, we feel that an environment built on these principles can ultimately serve to enrich the medical educational experience.

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